

OPTIMAL CONTROL OF WIDE CONVERSION RATIO SWITCHING CONVERTERS

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RELATED APPLICATIONS

This application is related to U.S. provisional application Ser. No. 60/404,967, filed August 22, 2002, in the name of the same inventors listed above, and entitled, "OPTIMAL CONTROL MEANS FOR AC/DC MULTICONVERTERS TO ACHIEVE HIGH INPUT POWER QUALITY AND TO ALLOW CONTROLLABLE DRIVE WAVFORMS" The present patent application claims the benefit under 35 U.S.C. §119(e).

BACKGROUND OF THE INVENTION

1. Field of the Invention

The present invention relates generally to control of power supplies, and more specifically to methods and apparatus for converting from a widely varying input voltage, such as a rectified AC voltage or a filtered DC voltage, to an output current or voltage.

2. Background of the Invention

Cascaded converters have been demonstrated which efficiently convert widely varying input voltages, such as a rectified AC input voltage, or DC voltages such as those found
5 in an automotive or truck battery voltage, to voltages or currents significantly larger or smaller than said inputs. Certain of these converters include a single switch cascaded converter such as a buck-boost-buck converter.

An efficient controller for these types of converters would
10 divide out changes in frequency with input line; would allow sensing the negative voltages associated with such topologies; and would contend with the widely varying currents or voltage magnitudes and polarities being sensed to feedback output information to these topologies.

15 An example application for such converters would be the driving of high power LEDs. These LEDs require a fixed DC current and may be dimmed either by varying the current magnitude or producing a current pulse train which is better for LED lifetime.

20 Solid state illumination sources, LEDs, capable of replacing incandescent and fluorescent lamps have recently been demonstrated. These LEDs last longer and are more efficient than existing sources, however, the heat they produce is conducted rather than radiated. The result is extremely high

operating temperature beyond the capability of standard power supplies containing electrolytic capacitors. Further, light fixtures typically do not have space for a power supply and a lamp, therefore to retrofit existing applications extremely
5 small power supply form factors must be created.

It would therefore be desirable to incorporate the above controller into an integrated circuit which can operate from high input voltages, stay operational for a non-filter input such as a rectified AC signal or a phase controlled AC signal,
10 and to provide open load, under voltage and other protections for the power supply. It would be desirable if the resulting supply was small enough to mount in retrofit form factors, is capable of high temperature operation for long periods of time, could regulate an output current, and could be mounted close to
15 the illumination source.

It would be desirable in one embodiment to provide a power factor corrected power supply such that the power supply looks to the AC line like a resistive element.

It would further be desirable in another embodiment to
20 reduce filter requirements by drawing constant power or near constant power through the converter so that input current varies inversely with instantaneous input voltage. To prevent over currents during the "cusps" or low voltages observed in an

rectified AC waveform, it would be desirable to engage a filter only once reaching a voltage low enough to allow use of low ESR capacitors so that filtering components values and sizes may be minimized and so that components such as electrolytics with poor
5 high temperature reliability may be eliminated from the circuit.

Therefore, it would be desirable to provide a method and apparatus for overcoming the problems discussed above.

SUMMARY OF THE INVENTION

In accordance with one embodiment of the present invention, a power supply circuit is disclosed. The power supply circuit has a switch state controller for producing a pulse train. A
5 frequency of the pulse train is controlled by a feedback signal coupled from an output characteristic of the power supply circuit. The switch state controller is coupled to one of an input or an internal node of the power supply circuit for controlling the on time of each pulse in the pulse train,
10 primarily to divide out frequency variation with input line changes.

In one embodiment the on time is varied inversely with the instantaneous input voltage to produce a constant power converter. In another, the on time is varied inversely with the
15 RMS value of the input to produce power factor correction when boost or flyback stages represent the first cascaded stage. Yet other embodiments allow sampling of internal nodes to set on time.

A plurality of cascaded converter stages is coupled between
20 the input and the output. Each of the cascaded converter stages have all switch control coupled to the switch state controller whereby each of the plurality of converter stages is switched by the pulse train.

In accordance with another embodiment of the present invention, the power supply circuit above is coupled to a feedback circuit. The feedback circuit comprises differential inputs wherein each terminal of the differential inputs is
5 coupled to a separate transconductor. A current sensing element is coupled to the differential inputs. The transconductors and the current sensing element allow selection of arbitrary voltage across the current sensing element and choice of polarity.

In accordance with another embodiment of the present
10 invention a frequency controller is disclosed. The frequency controller has a current detector coupled between a first transconductor and a second transconductor. A first integrator is coupled to the first transconductor. A second integrator is coupled to the second transconductor. A comparison device is
15 coupled to the first and second integrators. A charge pump coupled to the comparison device. A voltage-to-frequency converter coupled to the charge pump. A period of the frequency controller is adjusted in conformance with a detected current.

In accordance with another embodiment of the present
20 invention, a power supply circuit is disclosed. The power supply circuit has a rectifier coupled to an input of the power supply circuit for producing a rectified power signal from an AC input voltage. A plurality of cascaded converter stages is provided wherein a first of the cascade converter stages has an

input coupled to an output of the rectifier. The converter stages are used for providing conversion of the rectified power signal to a DC output, via charging and discharging of the energy storage elements. A switching device is provided for
5 switching the plurality of converter stages whereby an output of the power supply is maintained substantially constant as the rectified power signal varies in instantaneous amplitude. A switch state controller is coupled to the switching device so the on-time is varied inversely with an instantaneous rectified
10 AC amplitude and the period is set in conformity with a measured power supply output characteristic. The result is a near constant power converter. A protection feature to ensure that large currents are not drawn during the low voltages or "cusps" in the rectified AC waveforms requires the clamping of the pin
15 connected to the circuit controlling on time to a minimum voltage.

In accordance with still another embodiment of the present invention, a power factor correction device is disclosed. The power factor correction device has an integrated circuit
20 containing a switch state controller wherein the switch state controller is used for producing a pulse train. A frequency of the pulse train is controlled by a feedback signal coupled from an output characteristic of the power supply circuit. The switch state controller is coupled to one of an input or

internal node of a power supply circuit for controlling the on time of each pulse in the pulse train, wherein the switch state controller has a feedback circuit coupled to the switch state controller for controlling a frequency of the pulse train in conformity with an output characteristic of the power supply output. A resistor divider circuit is coupled to a rectified AC voltage source and to a pin coupled to a circuit controlling the on time. A filter is coupled to the resistor divider to produce a filtered DC voltage at said pin proportional to the RMS value of the rectified AC input voltage. A method to produce an undervoltage lockout for such a circuit as well as a method to maintain power to operate the circuits within the integrated circuit even when input voltage falls is also disclosed.

In accordance with another embodiment of the present invention, an open load or over voltage protection circuit is disclosed. The overvoltage protection circuit has an integrated circuit containing a switch state controller wherein the switch state controller is used for producing a pulse train. A frequency of the pulse train is controlled by a feedback signal coupled from an output characteristic of the power supply circuit. The switch state controller is coupled to one of an input or internal node of a power supply circuit for controlling the on time of each pulse in the pulse train, wherein the switch state controller has a feedback circuit coupled to the switch

state controller for controlling a frequency of the pulse train in conformity with an output characteristic of the power supply output. A clamp is provided for connecting one of an integrated circuit feedback transconductor terminals to a power converter
5 output voltage. A clamp is also provided from an output voltage to ground/common.

The foregoing and other objectives, features, and advantages of the invention will be apparent from the following, more particular, description of the preferred embodiment of the
10 invention, as illustrated in the accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1 is a schematic diagram depicting a prior art power supply.

Figure 2 is a schematic diagram depicting a power supply in
5 accordance with an embodiment of the present invention.

Figure 3 is a schematic of a controller integrated circuit
in accordance with an embodiment of the present invention.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

Referring to **Figure 1**, a prior art power supply is depicted. A bridge **BR1** full-wave rectifies an AC line input to produce an input power source. Filter capacitors **C1** and **C2** average the voltage at the output of bridge **BR1** to produce a DC voltage (approximately 360 Volts DC without load). Without filter capacitors **C1** and **C2** the power supply cannot change control function (e.g., duty cycle in a pulse-width modulated (PWM) power supply) as the input waveform varies in voltage from 0V to 360V. The control function dynamic range required to accomplish proper line regulation, which is the power supply's rejection of input voltage variation, is too wide for operation without filtering. An inductor **L1** is coupled between capacitors **C1** and **C2** to provide inrush protection and electromagnetic interference EMI filtering. A resistor **R1** is used to set the initial inrush current, providing a soft-start current to charge capacitor **C2** until the field produced in inductor **L1** collapses.

The power supply of **Figure 1** is of typical design well-known in the art as a flyback converter. A transformer **M1** couples energy from its primary side by the action of a switch implemented by a transistor **N1**. **N1** is controlled by a switch control **16**, typically a pulse-width modulator that varies duty cycle in conformity with a feedback signal provided from the circuit coupled to the secondary of transformer **M1**. A resistor

R2, a capacitor **C3** and a diode **D1** form a "snubber" circuit that absorbs the current spike produced when transistor **N1** is turned off that would otherwise produce a voltage spike on capacitor **C2** (and a spike on capacitor **C1** that will be reduced depending on
5 the characteristics of inductor **L1**).

The secondary side of transformer **M1** comprises a half wave rectifier implemented by a schottky diode **D2** and a filter formed by capacitor **C4** inductor **L2** and capacitor **C5**. The filter removes the higher harmonics of the switching waveform (pulse) that is
10 coupled from the primary side of transformer **M1** to the secondary. A zener diode **Z1** and optocoupler **OPTO1** provide a feedback signal to switch control, so that the pulse width of the signal controlling the gate of transistor **N1** may be varied to produce a constant voltage at capacitor **C5** as load current
15 and AC input voltage vary. A resistor **R3** is coupled across the output terminals of the power supply (load terminals) and is generally necessary to produce a stable no-load operating point, but may be unnecessary in some implementations, where the minimum pulse width of the switch is sufficient to produce a
20 stable no-load DC output.

The dynamic control range necessary to operate the power supply as described above without filter capacitors **C1** and **C2** is too wide for proper operation. For example, a 100Khz PWM switch-mode power supply would have to produce a pulse width of 5 μ s (50%

duty cycle) at an input voltage of .67V and a pulse width of 5ns
(.1% duty cycle) at an input voltage of 360V, in order to
provide the equivalent performance of a filtered-input converter
that can fully regulate it's control function on a pulse-by-
5 pulse basis. Both the efficiency of such a power supply and the
fast switching requirement at the low duty-cycle point make such
a solution impractical. Further, present-day switch-mode power
supplies typically switch at much higher frequencies, for
example 1Mhz, which exacerbates the above-described problem by a
10 factor of ten.

Referring to **Fig. 2** one embodiment of a power supply having
a switch state controller (**Fig. 3**) is shown. **E1 & E2** are input
terminals which may be coupled to an AC source, such as a pure
AC signal, a phase controlled AC signal or other signal. The
15 listing of the above should not be seen as to limit the scope of
the present invention. **L3 & C2** are a conducted emissions filter
meant to provide a high frequency path back to the power supply
for high frequency signals it generates and to provide a high
frequency impedance between the AC input and the power supply to
20 block higher frequency signals generated by the power supply.

A rectifier device **1** couples the AC signal to the power
supply input terminals. The power supply is a multiconverter.
There are two converter stages switched by a single switching
device, the switching device controlled by a controller

integrated circuit **3**. A buck second stage is shown but could be replaced by any second stage DC/DC converter.

The first converter stage has an input from the most positive terminal of the input rectifier and the drain of MOSFET **M1**. The second converter stage has an input from the anode of **D1**, cathode of **D2** and negative terminal of **C3** and the source of MOSFET **M1**.

C1 provides a low impedance path for high frequency signals associated with the switching of **M1**. There are two states, one when the switch **M1** is ON and one when the switch **M1** is OFF. During the ON state, inductor **L1** and diode **D9** are placed across the rectified AC voltage across the full bridge causing the current in **L1** to rise at a rate of $(V_{bridge} - V_{D9})/L1$. At the same time the voltage previously stored on **C3** is placed across the load, **2**, inductor **L2**, sense resistor, **R3**, and diode **D2**, causing the current to rise in **L2** according to $(V_{C3} - V_{load} - V_{D2} - V_{R3})/L2$. During the OFF state, **L1** transfers energy to **C3** through **D1** and **D9**. At the same time **L2** freewheels through **D3**, sense resistor **R3**, and the load, **2**.

Control circuit **U1** may be connected directly across the rectified DC input, or may be connected as shown in **Fig. 8**. This connection uses **M2** in a source follower configuration to provide undervoltage lockout and also to divide heating between **M2** and **U1**. A resistor divider **R4**, **R9** & **R5** is the reference for

the source follower and is programmed such that the source of **M2** will reach the under voltage lockout (UVLO) of the controller **U1** at the desired UVLO threshold of the filtered rectified AC input. Alternatively if a higher effective UVLO than programmed
5 into the integrated circuit, **U1**, is not needed and the integrated circuit package is thermally capable (the source follower transistor would otherwise handle a large portion of the thermal dissipation), then a high voltage regulator, **201**, within the integrated circuit **U1** may be connected directly
10 across the rectified AC input without the need for follower means, **M2**. Another option is to reference the source follower, **M2**, to a specific voltage for example using a shunt device **5**, so that the highest voltage rated capacitor which is not electrolytic (and therefore can operate at high temperatures),
15 **C6**, may be connected to its source. A blocking device such as a diode coupled from this source **D8**, which is also coupled to the integrated circuit **U1** regulator, **201**, may then be coupled to the input of the power supply as a energy reservoir (power source) during the time that the rectified AC input falls below the
20 capacitor voltage, **C10**. In such an instance an alternate signal conforming to the average or peak magnitude of the rectified AC input would need to be scaled and coupled to the **Von**, **pin 2** of integrated circuit **U1**. In an alternative embodiment where the ON time is varied instantaneously with the rectified AC input

voltage, this can reduce current spikes. In this embodiment it will reduce output filter requirements and reduce the size of the energy storage capacitor, **C3**.

An internal regulator coupled to **pin 1 of U1** is internally
5 coupled to **C6** which stores energy to provide a powering mechanism for **U1** during the time that the voltage on **U1 pin 1** falls below the voltage on **C6**. **C6** further provides a low impedance charge source to drive the switching MOSFET **M1**.

Pin 2 of control circuit **U1** is connected to a scaled and
10 filtered signal proportional to the rectified AC input. **U1 Pin 2** also controls the ON time of the MOSFET **M1**. By holding **U1 pin 2** at a substantially constant voltage for a given AC input magnitude, the on time of the switch will be substantially constant and therefore for a relatively fixed switching
15 frequency the average input current will be drawn in proportion with the input voltage - the result is high input power quality with PF > 90% and THD < 15%.

The control circuit **U1** includes a differential integrating feedback which works to achieve parity between two feedback
20 currents flowing out of **U1 pin 5** and **U1 pin 6**. To reach current parity it is necessary to produce a voltage at pin 5 such that $V_{pin5}/(R7+R_{th1})$ is equal to $(V_{pin6}-V_{R3})/(R1+R6+R8)$. This programming method allows a pseudo-programmable sense voltage, across **R3**, to be selected as desired based on the above current

balance. Rth1 illustrates that temperature dependent impedance devices such as an NTC or PTC may be used to adjust the feedback to provide the desired average current through the load at different temperatures.

5 The control circuit in **U1** produces independence between the feedforward and feedback sections of the circuit. The feedback maintains a substantially constant feedback voltage with **C5** & **C8** in combination with resistor **R1**, **R8** producing an optional low pass filter, which may not be needed depending upon the choice
10 of compensation components **C7** & **R2**, the size of **C3** & **L2**, in conformance with the acceptable ripple in the load, **2**. Resistor **R3** is the sense resistor. The sense resistor voltage to be regulated may be chosen to be large in magnitude, such as -2.5V to escape the noise floor or alternatively may be chosen to be
15 small such as -165mV to save energy. An innovative feedback means which includes comparing the voltage developed across matched integrators, **214**, does not require filtering of the feedback signal to close the loop.

 A capacitor **C9** is connected across the differential input
20 to provide a high frequency short. This is used to compensate for finite slew rates on the VCCS operational amplifiers which otherwise would cause a DC error (high frequency components within the bandwidth of the op amps but beyond its slew rates may have differing rise and fall slopes producing a net DC error

after integration).

Compensation is achieved using **C7** and **R2** coupled between the gate output and the differential input of **U1**. If **U1** is considered as a gain element from its differential input to the gate output, then it is easily seen that the **C7** and **R2** create a pole and a zero to allow compensation programming.

Protection is provided in three forms. Firstly there is a thermal shutdown or limit circuit with hysteresis, **222**, to protect against die overtemperature. There is an internal shutdown logic or restart means if the internal VCO control register reaches an upper limit (ie. the loop does not close within the charge up time of the VCO register, **221**). The third is an overvoltage clamp through **D6** means which pulls additional current from the **U1 pin 6** if the voltage across the load grows too large, to lower the frequency and quantity of energy transferred per cycle. **D5** and **D4** provide further overvoltage breakdown clamping if a fast overvoltage occurs more quickly than **U1** is able to react.

The multiconverter topology, due to the storage element, **C3**, and elimination of a **L1** discharge path to the input which would dissipate power, allows operation with a phase control signal, such as that produced by a typical wall dimmer. To use LED solid state lighting in retrofit applications it would be desirable if the LED drive signal were to dim and operate from

such an input signal. The circuit in **Fig. 8** will operate from such a signal if a peak detector, edge detector or averaging filter, **4**, is coupled to the rectified AC input so that a signal proportional to the extent of phase change is communicated.

5 This dimming signal may be coupled to **U1** through a resistor, **R11**, for example and summed into the differential feedback to change the average load, **2**, current to accomplish dimming. Whether operating from pure AC or from an phase controlled AC signal, the ripple through the load, **2**, may be programmed to any
10 desired level using one or more means including the choice of **C3**, the choice of compensation components **C7** & **R2**, a low pass filter coupled from the sense resistor, **R3**, to the differential feedback of **U1**, for example **R1**, **C5**, **R8** & **C8**, and/or through the use of an energy reservoir capacitor coupled to a follower, **M2**,
15 and through a diode to the power supply input.

In certain LED applications, such as where Kelvin temperature and CRI must be maintained at certain levels, it is desirable to maintain a constant current profile in the LEDs. This constant current is not the average current, but rather the
20 rise time and peak current operating in discontinuous mode. In other words a consistent current profile when current is flowing, even if current does not flow throughout the high frequency cycle. A second embodiment in which the load current, **2**, waveform is measured, for example by coupling a measuring

circuit to **L2**, whose peak current is maintained constant even while the average current varies to dim in **L2** DCM, may be used to maintain a constant color spectrum, CRI & Kelvin temperature while dimming.

5 In certain applications, it may be desirable to further modify the operating characteristics of the converter in conformance with optically measured parameters and/or temperature. In such a circumstance a PTAT signal may be coupled to the differential feedback of **U1** as may a signal
10 proportional to a measured color or intensity. Such measurements may be made with an optical meter fabricated on the same integrated circuit as the switch state controller with an optical aperture provided in the integrated circuit package.

 In certain applications it may further be desirable to
15 mount solid state LEDs capable of replacing light sources, near to the AC/DC power supply with controller, to produce a form factor capable of retrofitting existing lighting sources. High power ($\geq 1\text{W}$) LEDs produce too much conducted heat for the use of conventional power supplies, which contain electrolytic
20 capacitors, to operate for long periods of time in confined common lighting form factors, such as track fixtures, recessed downlights, or traffic light housings, etc. from which removal of heat is difficult.

Further, it is necessary to provide a mechanical means whereby the heat generated by LEDs and by the power supply may be conducted away to retain a reasonable operating temperature. Such a solution is possible using a multiconverter and controller, using the methods taught herein to eliminate the need for any electrolytic capacitors or components with short life at high temperatures ($>90^{\circ}\text{C}$), and by using the same heatsink, such as an aluminum substrate PCB board, to couple heat away from both the LEDs and from the power supply.

Examples of retrofit solutions which would utilize a multiconverter & controller in close proximity with the LED source would include MR16 form factor LED lamp replacements, small form factor lamps in elevators and vending machines, and PAR lamp replacements for traffic lights, recessed downlights, spot lights and track lights. The result would be high input power quality ($>90\%$ power factor, $<15\%$ THD), small size, long life at high temperature, and the 30% or less peak to average ripple desired in high power solid state LEDs such as the newly introduced Luxeon 1W or 5W White, Green, Amber, Blue & RED LEDs. The system would also be compatible with phase controlled AC dimming circuits commonly found in the incandescent electrical circuits likely to be targeted for solid state lighting retrofits to increase lamp life and efficiency.

While the invention has been particularly shown and described with reference to the preferred embodiments thereof, it will be understood by those skilled in the art that the foregoing and other changes in form, and details may be made
5 therein without departing from the spirit and scope of the invention.